

Maximising the ecological value of hard coastal structures using textured formliners



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ABSTRACT

In order to enhance the ecological value of vertical hard coastal structures, hybrid designs with complex surface textures (such as a combination of grooves and pits) have been recommended. This strategy optimises ecological colonisation at two spatial scales: 1) at the mm-scale for barnacle abundance (shown to have bioprotective capabilities), and 2) at the cm-scale for species richness and abundance through the incorporation/creation of habitat features. To determine the optimal design for improving the intertidal habitat quality of vertical coastal defence structures, we conducted an ecological enhancement trial involving 160 artificial concrete tiles of different designs (and thus topographic complexity) and 24 cleared natural surfaces (150 × 150 mm) at three sites in the UK. Within 18 months, tile designs with intermediate levels of complexity (mm-scale surface roughness) were optimal in increasing barnacle cover compared to plain-cast tiles. Tiles with high complexity (with microhabitat recesses up to 30 mm deep) developed greatest species richness and mobile species abundance and had lowest peak air temperatures and highest humidity. Such textured ecological enhancements can help improve the habitat value of existing and future hard coastal structures by favouring the conservation of intertidal species in urban marine habitats and enhancing otherwise weak or absent ecosystem service provision.

1. Introduction

Coastal and estuarine environments worldwide are under increasing pressure from a variety of human and environmental factors, including coastal urbanisation and climate change related impacts, such as sea level rise and increased storm events. In response, the number and extent of concrete coastal marine structures has increased over recent decades, particularly in intertidal and shallow subtidal zones (Airoldi et al., 2005; Heery et al., 2017). The proliferation of structures has major well-documented geomorphological (landforms and how they vary in space and time) and ecological implications, such as lowering of fronting beach surfaces, narrowing the intertidal and shallow subtidal zones and compromising the potential area for species colonisation, thereby resulting in the loss of species diversity (Chapman and Underwood, 2011; Jackson and McIlvenny, 2011).

Distinct assemblage differences occur between natural and artificial habitats (Bulleri and Chapman, 2010; Chapman and Blockley, 2009);

hard coastal marine infrastructure are often found to host lower species diversity and abundance compared to natural habitats (Bulleri, 2005; Coombes et al., 2015; Lai et al., 2018). One key underlying reason for this variation in species assemblage is the difference in topographic complexity of the substrate and its associated habitat together with a lack of geomorphic complexity (i.e. the spatial variation of landforms and land-forming processes operating on a rocky coast). Artificial structures are typically designed as plain-cast and lack the habitat structural complexity (hereafter complexity) associated with the geodiversity of natural rocky shores such as fine-scale (mm-cm) surface roughness, grooves (mm) and microhabitats (cm). Another key factor influencing the success of intertidal organisms, particularly higher up in the tidal frame, is risk of desiccation (Cartwright and Williams, 2012), which is closely linked to microclimate. Material properties (Coombes and Naylor, 2012) and habitat complexity are known to influence local microclimatic conditions, affecting desiccation risk (Meager et al., 2011), resulting in different patterns of ecological colonisation. Thus,

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the complexity of hard structures potentially also influences the microclimate as well as the physical habitat available for intertidal species.

Artificial structures thus function as poor ecological surrogates of natural surfaces (Firth et al., 2014b). Ecological enhancement is the process of modifying engineering designs to optimise ecological gains, largely through improving the quality or quantity of habitat available (Hall et al., 2018). For instance, the incorporation of surfaces and textures that mimic rocky coasts into the design of structures can improve their capacity to host a variety of species. Such manipulations improve the ecological value of coastal marine infrastructure by enhancing multifunctionality (Naylor et al., 2012a). For example, Coombes et al. (2017) have shown how the presence of barnacles can reduce the impacts of weathering and erosion through bioprotection.

Previous surface texture trials have found that manipulation of complexity at the mm-cms scale resulted in gains in species richness and abundance. Coombes et al. (2015) compared smooth designs to mm-scale grooved designs, finding that these intermediate complexity levels on nearly horizontal surfaces resulted in significantly greater barnacle abundance after one settlement season. This is important as early colonising species aid in the development of more diverse species assemblages (Coombes et al., 2015) and moderate the surface microclimate (Coombes et al., 2017). High (cm-scale) and intermediate (mm-scale) complexity surfaces develop significantly greater macro-invertebrate abundances and more diverse communities than smooth surfaces (Moschella et al., 2005; Prendergast et al., 2009), however these results are moderated by site-specific factors.

Increasing complexity through the addition of roughness and microhabitat provision has the potential to increase the ecological value of artificial designs. On artificial structures, rock pools at the 1–100 cm scale have been found to have twice the number of species than freely draining areas (Moschella et al., 2005) and the addition of small pits (cm-scale) and recesses served to increase species richness compared to control tests (Firth et al., 2014b). On natural rocky shores, crevices, pits and holes function as important habitats for marine organisms and are important in the development of communities, providing refuge from environmental stressors (including desiccation stress), predation, scouring and sedimentation (Prendergast et al., 2009; Firth et al., 2014b; Rickards and Boulding, 2015). Ecologically enhanced designs aimed at mimicking natural habitat structural complexity have been shown to greatly improve habitat quality, particularly high up in the intertidal zone where exposure time and stress is greater (Chapman and Blockley, 2009). Availability and improved microhabitat quality (e.g. increased water retention) on these structures can result in greater biodiversity (Browne and Chapman, 2011; Firth et al., 2014a; Evans et al., 2016; Loke et al., 2019).

The addition of cm-scale habitat features such as grooves (Hall et al., 2018), pits (Loke et al., 2017) and pools (Firth et al., 2014b) is simple and relatively inexpensive, with several trials showing a sevenfold increase in biodiversity compared to traditional plain-cast, smooth surfaces (Naylor et al., 2017). However, improving the habitat value of artificial structures using ecologically enhanced designs depends on how successfully the complexity (surface roughness and microhabitats) of natural rocky shores are replicated, including the orientation of features.

Vertical coastal marine structures are often selected as test sites for tile installations, as under existing sea level rise scenarios, these structures are intended to function as a physical erosion or flood barrier spanning the upper shore zones (Bellgrove et al., 2013). However, the smooth, near-vertical surfaces provided by these structures present an alien and unsuitable habitat for many species, reduce intertidal habitat availability and contribute to coastal squeeze (Jackson and McIlvenny, 2011). Microhabitats on natural rocky shores can offer cooler and more humid microclimates (Jackson, 2010) than would be expected on smooth vertical surfaces, highlighting that enhancing vertical structures present the greatest opportunities for ecological gains. Much work has

already been done on vertical structures, such as manipulating mortar to create new habitat at Shaldon (UK) (Firth et al., 2014b), omitting blocks (Chapman and Blockley, 2009) or retrofitting habitat in Sydney, Australia with flowerpots (Browne and Chapman, 2011). In a review of existing ecological engineering studies, 67% of 109 studies looked at retrofitting onto existing structures whereas only 23% focused on texture (Strain et al., 2017). Many coastlines are too exposed to retrofit structures due to greater wave exposure. Where there is limited capacity for larger scale ecological enhancements (such as managed realignments) or where retrofitting is unsuitable on engineering grounds, fitting textured form liners (liners used to prepare designs on concrete walls) onto vertical surfaces offers an important alternative that can be used in a variety of settings including exposed conditions. Although the work reported here was tested in moderately exposed conditions, it acts as a signpost for enhancement where other designs would likely be unsuitable.

To our knowledge, the field experiment reported here represents one of the largest ongoing ecological enhancement trial of its kind in the UK. It was undertaken to determine which surface textures on hard vertical coastal marine structures are best placed to maximise the ecological potential for rocky shore species, as measured by species richness (mobile and sessile species, excluding barnacles) and barnacle cover (%). To evaluate the differences in microclimatic buffering provided by different designs we recorded temperature and humidity data, thus enabling an assessment of how different scales of ecological enhancement affect habitat quality in terms of both physical habitat space and microclimate.

Eight tile designs were created (in addition to clearing tile-sized areas on the structure surface) and these designs were installed at various sites in the UK. The designs varied in their complexity in terms of fine-scale surface roughness and microhabitat availability, from mm to cm scale. All but two designs (Singapore and Art 1) aimed to increase potential ecological value by replicating the topographically complex features of rocky shores that most influence species recruitment or community composition (Coombes et al., 2011). The Singapore tile design, previously tested in a separate experiment in tropical Singapore, was used here to examine the applicability of this design to a temperate region and provide the greatest number of microhabitat features. The Art 1 design was created to mix art with ecology and create innovative new habitat for rocky intertidal species that would allow the public to be more artistically engaged with ecological enhancement work. The remaining 6 designs replicated topographically complex features of rocky shores, including a rapidly manufactured mm-scale grooved design (similar to fine-scale cracks on natural rocky shores), proven to significantly enhance barnacle settlement since the grooves are a suitable size relative to the settling organisms body size (Coombes et al., 2015). Similarly, the barnacle design scaled up the profile of settled barnacles, taking design inspiration from nature (biomimicry). All of the concrete designs are readily scalable being developed from computer-generated files or easily converted to digital and thus scalable to whole walls, such as the Art designs.

2. Materials and methods

Prior to tile installation, baseline surveys were visually conducted in the mid-upper intertidal zone at each site (approximately between 2 and 3.06 m above mean lower low water (MLLW)). These surveys were conducted on the initial scoping visit to each site, with $n = 5$ (100x100mm) quadrats used per site. This provided an insight into baseline barnacle cover (%) and species richness (mobile, excluding barnacles, no other sessile species recorded).

Between late April and early May 2016, tiles were installed in the mid-upper intertidal zone on selected artificial structures at three UK sites (Fig. A1). At site 1, Blackness Castle (56°0'24.4614"N, 3°30'55.9362"W) in the Firth of Forth in Scotland, tiles were installed on the north-eastern face of a concrete pier extending into the Firth.

Table 1
Experimental Designs.

Design	Complexity	Description
Clearing	“Low” (control)	150 × 150 mm patch clearings on structure surfaces using paint scraper and wire brush. After washing over one tide, the cleared patches were blowtorched to remove biofilm.
Control (Smooth, plain-cast concrete)	“Low” (control)	This tile acts as a procedural control for comparison with cleared controls and moulded tile designs; plain-cast surface replicates the smooth finish typical of pre-cast concrete armour and seawall units.
Grooved	“Intermediate”	Coarse wire brush dragged across drying concrete to create a series of mm-scale ridges after Coombes et al. (2015), 3D-scanned and the grooves enlarged to allow design replication in large scale future projects.
Barnacle	“Intermediate”	Mm-scale relief replicating the barnacle profile and shape including grooved surfaces of different orientations (design by Daniel Metcalfe, University of Falmouth using (MAKERNOW, 2016)) and design resized to 150 mm × 150 mm for this study.
Art 3	“Intermediate”	Crushed-foil cast, no mould. Textured surface more similar to natural rocks.
Geotile	“High”	TLS Leica C10 scans of rock features (cracks and crevices) on a boulder. The height of these features was exaggerated and then 3D printed so that the relief was approximately 30 mm.
Singapore	“High”	Modified version of a tile design trialled in Singapore. Design was created using software ‘Complexity for Artificial Substrates’ (Loke et al., 2014) to allow variation in the dimensions of each microhabitat feature (depth and width of pits and grooves).
Art 1	“High”	‘Chevron’ pattern using silicon moulded from folded paper.
Art 2	“High”	Trowel handle pushed into sand to create microhabitats with the sand-cast design then used to create a silicon mould.

Site 2 was on a north-western facing concrete seawall at Saltcoats Harbour, North Ayrshire, Scotland (55°37'51.4"N, 4°47'13.4"W). Site 3 was a north-eastern facing concrete groyne in Shanklin (50°38'00.0"N, 1°10'08.5"W) on the Isle of Wight, England. The mid-upper intertidal zone was selected due to the disproportionate loss of habitat at this shore height resulting from the insertion of coastal marine structures (Dugan and Hubbard, 2010). At this shore height, artificial structures support lower species richness than on natural rocky shores of comparable heights (Green et al., 2012).

Five of the eight ecologically enhanced 150x150mm tile designs (“Control”, “Grooved”, “Barnacle”, “Geotile” and “Singapore” (see Table 1 for descriptions) were developed in line with engineering standards of practice using a standard marine concrete mix (CIRIA, 2010). Silicon moulds were used during the casting process to create 112 marine concrete tiles (experimental designs in Table 1). Three more designs (“Art 1”, “Art 2”, “Art 3”) were created using Vicat Prompt Natural Cement, with 48 tiles constructed using this material. Despite the Vicat material tiles being unsuitable for use in large-scale construction, the castings provide contextual information on optimal designs for ecology.

All the designs created focused on the interrelationships between complexity (such as surface roughness and microhabitats i.e. pits and crevices) and biodiversity on rocky shores, drawing from marine ecology (Firth et al., 2014b) and biogeomorphology concepts (i.e. the two-way interactions between organisms and their habitat) (Naylor et al., 2012b). Each design varied in complexity (and surface area), providing a gradient from “Low” (plain-cast/clearing), to “Intermediate” (mm-scale modifications to surface roughness), to “High” complexity (microhabitats provided or with areas of relief > 10 mm) (Table 1). Designs are hereafter referred to as having low, intermediate or high complexity. Note, in this paper, the effect of complexity is not disentangled from area. The maximum feature depth was 30 mm on the Singapore tile and the maximum relief was approximately 30 mm on the Geotile. Fig. 1 shows each design in detail.

The installation strategy was consistent across the three sites. Structures were divided into four separate sections to allow an even distribution of tile designs across the length of the structure (Fig. A1). Two replicates of each design were installed in each section, resulting in a total of eight replicates of up to eight designs (including clearings) per site. Tile attachment points were delineated within the mid-upper intertidal zone on each structure and were scraped clear of visible organisms and left to be washed over by one tidal cycle. Following this, all cleared areas were burned with a butane blowtorch to remove existing biofilm and allow all designs and clearings to start from a common baseline (Green and Crowe, 2013). Each attachment point was assigned a number and designs were selected in rotation by random

number generator to maximise randomisation (Coombes et al., 2015; Herbert and Hawkins, 2006).

Spatial restrictions at Blackness resulted in $n = 7$ designs installed because the wooden panels dividing the structure into 1 m wide sections interfered with the adopted $1.5 \times$ tile length separation distance installation strategy. For tiles installed at other sites, 24 replicates were made (Table 2). However, financial restrictions meant that it was not possible to deploy 24 tiles of each design and so some designs were installed at only two sites ($n = 16$ replicates made, Table 2).

The textured surface of each tile was photographed at each site at 2, 6, 12 and 18 months post-installation to capture barnacle settlement and species richness patterns. Barnacle percentage cover and species richness (mobile and sessile, excluding barnacles), counted from presence/absence of species, were analysed using ImageJ, with photographs cropped to the 120 mm × 120 mm internal section of the tiles and the outer 30 mm excluded to account for potential edge effects (after Bulleri, 2005). The total number of mobile and sessile species (excluding barnacles) were recorded using the count tool across the whole surface of the cropped tile while barnacle cover (%) was calculated by delineating barnacles (or empty space where this was more frequent) and using the measure function, which was then converted to a percentage of overall tile area.

To determine whether microhabitats provided a cooler and more humid environment than tile surfaces at each site, relative humidity loggers (Hygrochrons™) were attached to tile surfaces using adhesive putty for sampling over one single low-tide event on a dry, sunny day in summer 2016. Loggers were attached to the centre of $n = 1$ of each tile design (due to limited number of Hygrochrons), with an additional logger placed in one of the holes on the Singapore tile (hereafter, microhabitat) and where possible, in the crevice on the Geotile and Art 2 holes. Humidity and temperature readings were recorded at 1 min intervals over two-three hours (Blackness and IOW, $n = 120$ readings, Saltcoats = 180 readings) with a $\pm 0.6\%$ resolution for humidity (Coombes et al., 2013) and $\pm 0.5^\circ\text{C}$ for temperature.

2.1. Statistical analyses

Generalised least squares (GLS) and linear mixed effect (LME) models were used to analyse the continuous variables of barnacle cover (%), species richness (mobile and sessile, excluding barnacles) and mobile species abundance data with respect to the categorical variables of tile type by months after installation. Models were applied to each site separately to determine whether the differences in barnacle cover and mobile and sessile species richness (excluding barnacles) were influenced by the concrete tile designs ($n = 9$ including clearings). We analysed each site separately due to very large site differences. GLS and

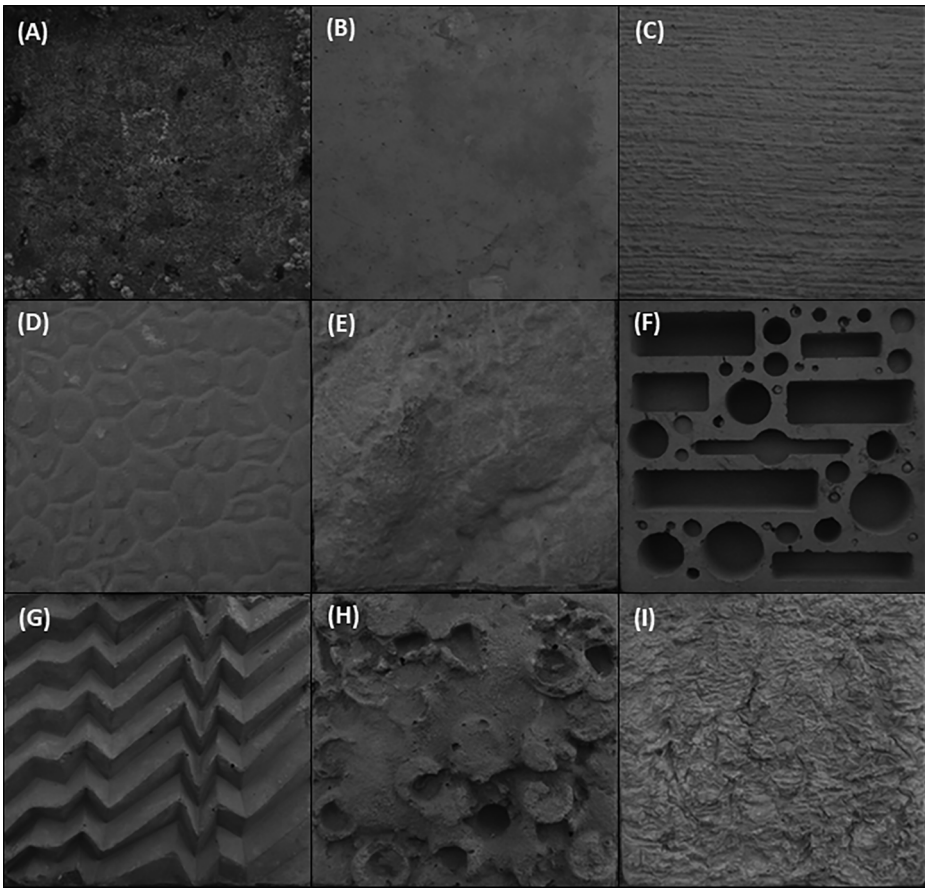


Fig. 1. Textured surfaces (150 × 150 mm) of a natural clearing tile area and the tile designs (A) Clearing, (B) Control(smooth), (C) Grooved, (D) Barnacle, (E) Geotile, (F) Singapore, (G) Art 1, (H) Art 2, (I) Art 3.

Table 2
Sites and number of replicates of each tile design that was installed at each location.

Design	Site	Replicates made (n = 8 per site)
Control	All	24
Grooved	All	24
Barnacle	All	24
Geotile	All	24
Singapore	Blackness, Saltcoats	16
Art 1	Blackness, Isle of Wight	16
Art 2	Saltcoats, Isle of Wight	16
Art 3	Saltcoats, Isle of Wight	16

LME models were compared using the `anova()` function in R [Pinheiro and Bates, 2009](#), with fixed effects kept the same for comparison. Model selection was then based on the most suitable model with the lowest Akaike Information Criterion (AIC) ([Zuur et al., 2009](#)). Least-squares means were conducted for post-hoc pairwise comparisons after applying Tukey’s multiplicity adjustment ([Lenth, 2016](#)). This allowed for individual comparisons between designs with months after installation, with all tests performed at the 95% confidence level. A full table of significant barnacle percentage cover results can be found in [Table A1](#). Eighteen month species richness (mobile and sessile, excluding barnacles) and mobile species abundance data was used. A full table of significant results for species richness and mobile abundance at 18 months can be found in [Tables A2 and A3](#) respectively. Kruskal-Wallis tests were used to determine differences between temperature and relative humidity (%) over a single two-three hour low tide period with tile type at each site. All analyses were carried out in R version 3.5.1 ([R Development Core Team, 2018](#)).

3. Results

3.1. Baseline surveys

From baseline surveys, three species of barnacles were recorded at the sites surveyed, *Semibalanus balanoides*, *Autrominius modestus* and *Chthamalus montagui*, with *Autrominius modestus* the only non-native species recorded. All three species were recorded at Saltcoats and the Isle of Wight, although Saltcoats only had a few *Chthamalus montagui* at mid-shore. At Blackness, *Semibalanus balanoides* and *Autrominius modestus* were recorded as *Chthamalus montagui* was out of its geographical range ([Crisp et al., 1981](#)).

Distinction between these three species was not made for this study due to the quality and resolution of tile images and the small size of newly settled barnacle spat that did not allow consistent identification of barnacles on tiles to species levels during the duration of monitoring. Each species breeds at a different time of year, with *Semibalanus balanoides* arriving from April through to the end of May, *Autrominius modestus* from May to October and *Chthamalus montagui* commencing in August in the English channel and September in the Clyde. These species do not have any functional differences as they are all suspension feeders. They have minor differences in their preferred habitats (i.e. *Autrominius modestus*- wave sheltered, high suspension load, *Chthamalus montagui*- usually open coasts and *Semibalanus balanoides* ubiquitous but rare in extreme wave conditions).

Barnacle cover varied considerably between sites. At Blackness, barnacles occupied an average of 99.20% (± 0.16 SE) of available space, a value that was consistent across the height of the installed tiles, possibly resulting from its more sheltered estuarine location. In contrast, Saltcoats had an average of 44.09% (± 6.67 SE) barnacle cover

Table 3

Summary of pairwise comparisons used in results section comparing barnacle cover (%) on tile designs at each site with months after installation (2, 6, 12, 18). Arrows indicate direction and extent of significance with comparison (e.g. Clearing > Control), > > > = $p < 0.001$, > > = $p < 0.01$, > = $p < 0.05$, NS = Not significant, X = one design was not installed at this site and so comparison could not be made.

Comparison	Blackness				Saltcoats				Isle of Wight			
	2	6	12	18	2	6	12	18	2	6	12	18
Clearing-Control	> > >	> > >	NS	NS	> >	> > >	>	NS	> > >	> > >	> > >	> > >
Grooved-Control	> > >	> > >	> > >	>	> > >	> > >	> > >	>	> > >	> > >	> > >	> > >
Barnacle-Control	> > >	> > >	> > >	>	NS	> >	>	NS	> > >	> > >	> > >	> > >
Art 3- Control	X	X	X	X	> > >	> > >	> > >	NS	> > >	> > >	> > >	> > >
Art 2- Control	X	X	X	X	> > >	> > >	> > >	> > >	> > >	> > >	> > >	> > >
Barnacle- Art 1	> > >	> > >	> > >	> > >	X	X	X	X	NS	>	> > >	> > >
Barnacle- Singapore	> > >	> > >	> > >	> > >	NS	>	NS	NS	X	X	X	X
Grooved- Art 1	> > >	> > >	> > >	> > >	X	X	X	X	>	> > >	> > >	> > >
Grooved-Singapore	> > >	> > >	> > >	> > >	> > >	> > >	> > >	>	X	X	X	X
Grooved- Geotile	> > >	> > >	>	NS	>	>	NS	NS	> > >	> > >	> > >	>
Clearing- Singapore	> > >	> > >	> > >	> > >	>	> > >	NS	NS	X	X	X	X
Control- Singapore	NS	> > >	> > >	> > >	NS	NS	NS	NS	X	X	X	X
Art 3- Singapore	X	X	X	X	> > >	> > >	> > >	NS	X	X	X	X
Art 2- Singapore	X	X	X	X	> > >	> > >	> > >	> > >	X	X	X	X
Grooved- Barnacle	NS	NS	NS	NS	NS	NS	NS	NS	>	> > >	>	NS
Grooved- Art 3	X	X	X	X	NS	NS	NS	NS	NS	NS	NS	>

possibly reflecting the young age of the structure (half of this section of seawall was constructed a couple of years prior to installation). The Isle of Wight, a more open coast site, averaged 56.83% (± 10.59 SE) barnacle cover across the structure.

Species richness counts, excluding barnacles, indicated that the sites were relatively species-poor, with the Isle of Wight having a maximum two species recorded (*Littorina littorea* (1 ± 0.55 SE), *Patella vulgata* (3.4 ± 1.12 SE)) and three species at both Saltcoats (*Nucella lapillus* (0.2 ± 0.2 SE), *Patella vulgata* (1.2 ± 0.74 SE) and *Littorina littorea* (1.4 ± 0.75 SE)) and Blackness (*Patella vulgata* (0.2 ± 0.2 SE), *Littorina saxatilis* (0.8 ± 0.37 SE) and *Littorina littorea* (2 ± 1.52 SE)). The average abundance of each of these species per quadrat (recorded in brackets) was low at each site. No sessile species apart from barnacles were recorded in these surveys.

3.2. Barnacle cover

Results are presented comparing barnacle cover (%) between tile designs within each site (Table 3). Early stage recruitment of barnacles was slower on the smooth control tiles than on textured tile treatments at all sites (Fig. 2). Plain-cast control tiles were found to underperform compared to all designs, at all sites, especially those with mm-scale surface roughness (grooved, barnacle, Art 3 tiles). For example, on the Isle of Wight the grooved, barnacle and Art 3 designs outperformed smooth control plain-cast tiles across all surveys up to and including 18 months post-installation ($p < 0.001$). Control tiles also performed poorly compared to clearings, which were rapidly colonised at all sites (Table 3). Clearings also equalled several of the designs in their ability to attract high barnacle cover (Fig. 2).

The “High” complexity designs (i.e. Art 1, Geotile and Singapore) attracted fewer barnacles than those of intermediate complexity (Fig. 2, Table 3). At all months post-installation grooved and barnacle designs had greater numbers of barnacles than the designs with greatest complexity (Art 1 and Singapore) at Blackness ($p < 0.001$, Fig. 2). On the Isle of Wight, the grooved design was shown to provide a better settlement surface for barnacles than the Geotile and Art 1 designs across all sampling periods ($p < 0.01$). At Saltcoats this difference was observed up to 6 months post-installation between the grooved and Geotile designs ($p < 0.05$) and 18 months between the grooved and Singapore designs ($p < 0.01$).

In particular, the Singapore design, the most complex of all the tiles, attracted fewer barnacles than the clearings at Blackness even after 18 months post-installation ($t(196) = 5.078$, $p < 0.001$) and at

Saltcoats up to 6 months post-installation ($p < 0.01$). The Singapore tile was also less suitable for barnacle colonisation than the control tiles at Blackness from 6 to 18 months ($p < 0.01$, Table 3) and did not differ from the control tile during surveys at Saltcoats. Barnacle cover (%) on the Art 2 design did not differ from designs of intermediate level complexity (grooved, barnacle, Art 3) at Saltcoats or the Isle of Wight. The Art 2 design also attracted more barnacles than the Singapore and control tiles across all sampling periods at Saltcoats ($p < 0.001$) and control tiles across all months at the Isle of Wight ($p < 0.001$).

Out of all designs examined, the intermediate complexity (mm-scale surface roughness) of the grooved tile was found to be the optimum design for early-stage recruitment and colonisation of barnacles (Fig. 3). On the Isle of Wight, grooved tiles had greater barnacle cover than barnacle tiles during the first year of installation ($t(219) = 3.496$, $p < 0.05$) and Art 3 exclusively at 18 months post-installation ($t(219) = -3.103$, $p < 0.05$). Although statistically insignificant, the grooved tile outperformed the barnacle design at Saltcoats and Blackness.

3.3. Species richness and abundance

The greatest abundance and largest number of species (mobile and sessile, excluding barnacles) was recorded at Saltcoats on a Singapore tile at 18 months post-installation, with 27 counts of $n = 4$ mobile species (Fig. 4) (11 *Melarhaphé neritoides*, 14 *Littorina littorea*, one *Littorina saxatilis* and one *Littorina obtusata*) and one sessile species (29.78% cover of *Ulva* sp). Tiles with intermediate complexity had a maximum of 3 species recorded across all survey months at all sites (Fig. 4), typically from the Gastropoda class (i.e. *Littorina littorea*, *Littorina saxatilis*, *Littorina obtusata*, *Gibbula umbilicalis*, *Nucella lapillus*, *Patella vulgata* and *Melarhaphé neritoides*) and ephemeral green algae (*Ulva* sp.). Small amounts of *Fucus spiralis* had also begun to colonise a microhabitat on an Art 2 tile at Saltcoats at 6 months (0.36% cover) and two Art 2 tiles at 12 months (mean = 0.80%). At 18 months at Saltcoats, *Fucus spiralis* was found inside microhabitats features on two Singapore tiles (mean = 3.3%) and on one Art 2 tile (0.21%). One individual *Carcinus maenas* was additionally observed in a Singapore tile at 2 months and another at 6 months post-installation.

At Saltcoats, the Singapore tile had significantly greater species richness and mobile abundance at 18 months post-installation ($p < 0.001$) than the control, grooved, barnacle and geotile designs ($p < 0.001$) (Fig. 4). At Blackness, the Singapore tiles had significantly greater species richness than the barnacle and geotile designs

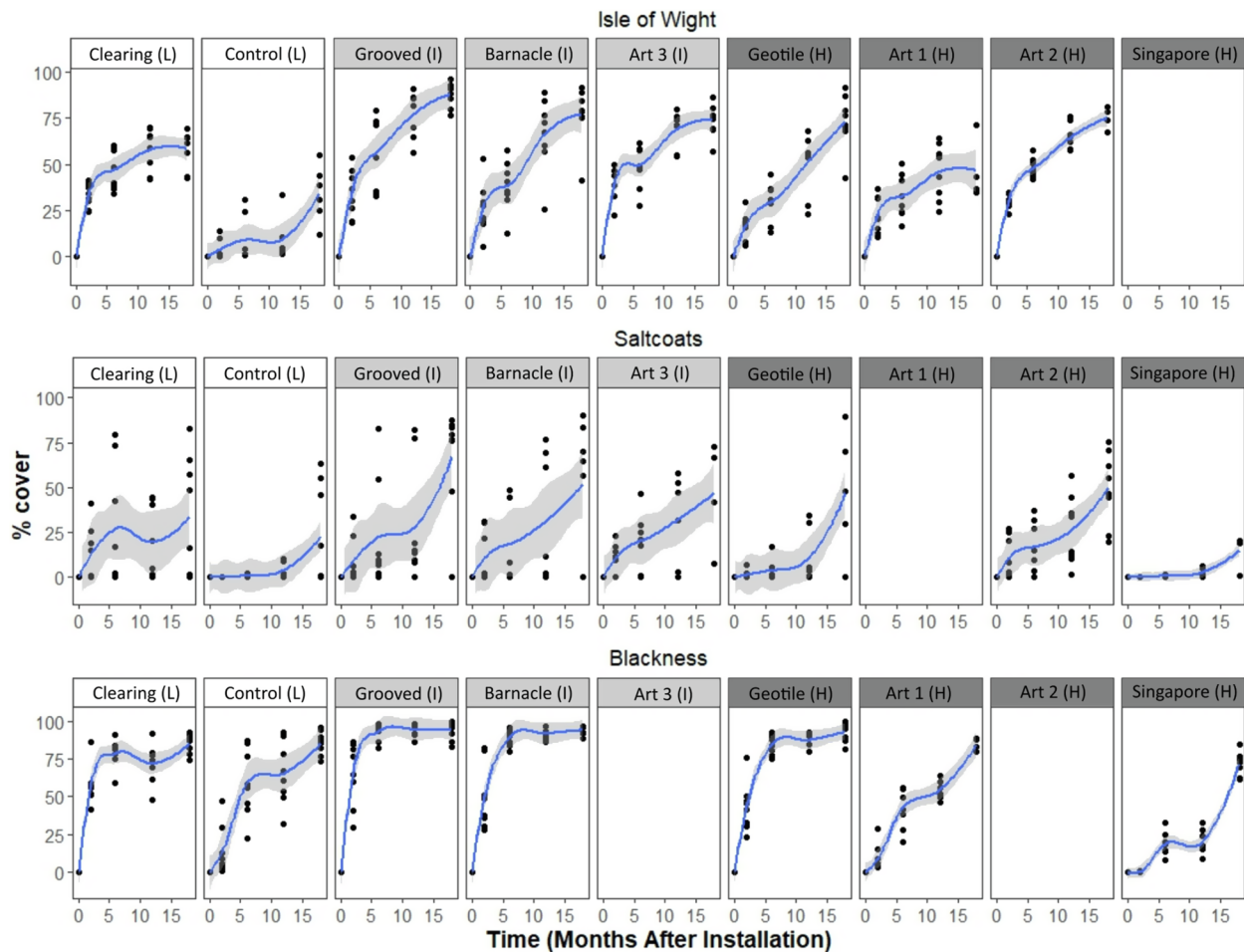


Fig. 2. Barnacle percentage cover 2, 6, 12 and 18 months post-installation (installed between April and May 2016) at the Isle of Wight, Saltcoats and Blackness with panels showing designs and complexity level indicated in brackets (L = low, I = intermediate, H = high) and shading. Grey band width indicates 95% confidence interval. Blank boxes indicate designs not installed at that particular site.

($p < 0.001$). On the Isle of Wight little difference occurred between tile types but the Art 1, 2 and 3 designs had greater species richness than the control tiles ($p < 0.05$). Although statistically insignificant for species richness, the Art 2 design exceeded the control, grooved, barnacle and geotile designs at Saltcoats in terms of macrofauna abundance ($p < 0.001$). On the Isle of Wight, all designs had greater mobile species abundance than control tiles ($p < 0.001$). Overall, the best design for species richness and abundance is the Singapore tile, with the Art 2 design also performing well (Fig. 5).

3.4. Microclimate

In examining all the data from the single two-three hour low tide period at each site, there was a significant difference in both humidity and temperature data on tile surfaces between tile types at all sites ($p < 0.001$).

Tile design was found to influence overall microclimate at the scale of individual test tiles. The tile design with the highest amount of microhabitat features (Singapore) was found to have higher humidity and lower temperatures than all tiles with fewer microhabitat features at

Saltcoats and Blackness ($p < 0.001$). The second most complex design in terms of microhabitat features (Art 2) also had higher humidity in microhabitats than control, grooved and barnacle designs at the Isle of Wight and Saltcoats ($p < 0.001$) and a lower temperature than clearings, barnacle and grooved tiles at Saltcoats and control, grooved and geotile (crevice) tiles at the Isle of Wight ($p < 0.001$). Of the designs examined, the control and grooved tiles frequently had lower humidity and higher temperatures than several other designs at each site.

The tile surfaces of the two most complex designs with microhabitats (Singapore, Art 2, Fig. 1) also had better microclimatic conditions (higher humidity and lower temperature) than several tile designs at Saltcoats. The surface of the Art 2 tile had higher humidity than clearings, barnacle and control tiles ($p < 0.001$) and lower temperatures than clearings, control, barnacle, grooved and geotile (crevice) ($p < 0.001$). This was also true of the Singapore surface, which in addition to the aforementioned designs at Saltcoats, additionally had a higher humidity than the Art 2 (surface), Art 3, geotile (crevice) and grooved designs ($p < 0.001$) and lower temperatures than the Art 2 tile (surface and microhabitat) and Art 3 designs.

In addition to altering the microclimate at the tile scale, significant

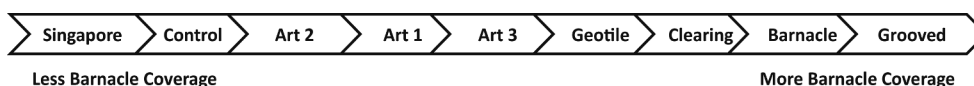


Fig. 3. Schematic of optimal designs for barnacle cover from least to most (left to right). Calculated from mean barnacle cover (%) on each tile type, averaged for all sites across all months (2, 6, 12 and 18) to show overall pattern.

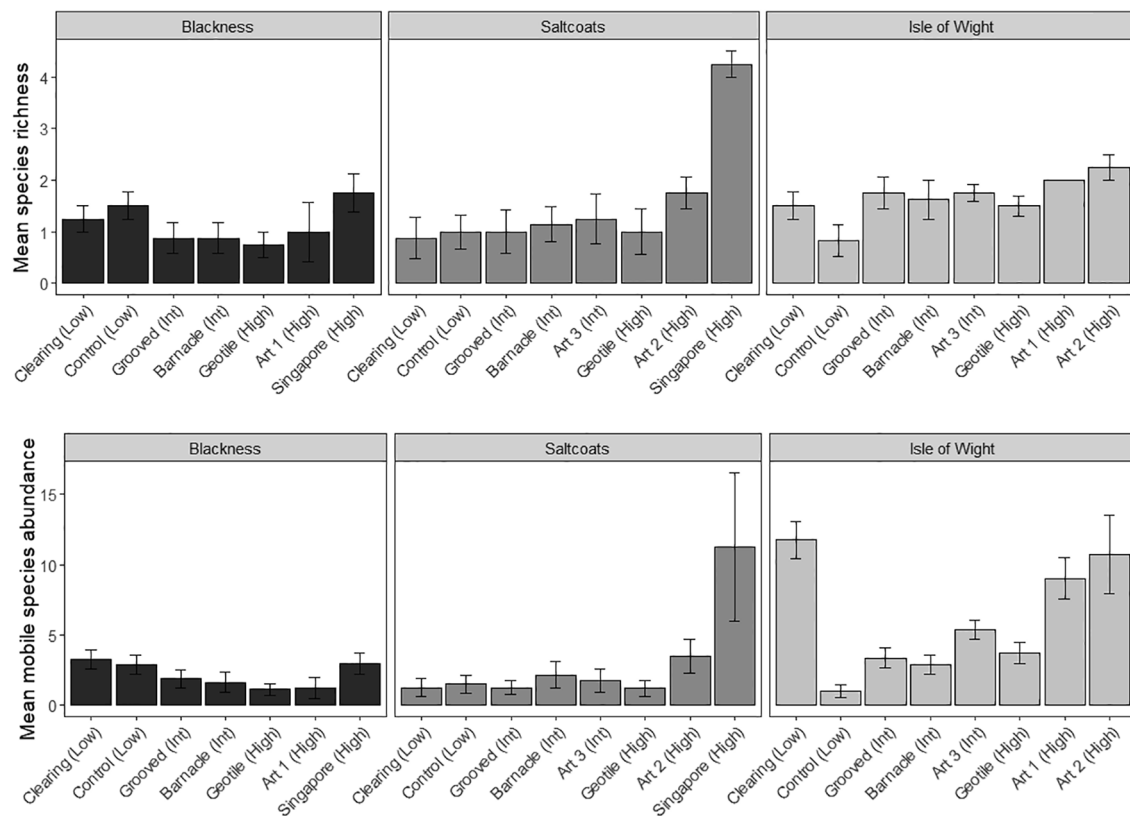


Fig. 4. Mean species richness and mobile abundance at 18 months post-installation (installed between April and May 2016) at Blackness, Saltcoats and the Isle of Wight (Mean \pm S.E.).

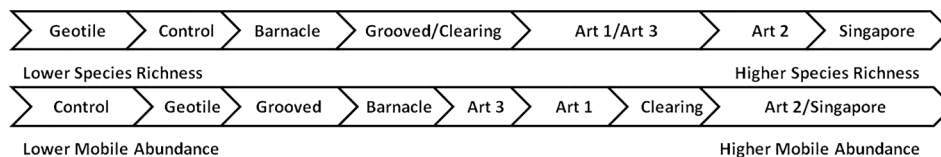


Fig. 5. Schematic of optimal designs for species richness and mobile species abundance from least to most (left to right), calculated as an average of values at 18 months, combined for all sites.

differences between microhabitats and the tile surface were found, with humidity higher in the microhabitat than on the Singapore tile surface ($p < 0.001$). Microhabitat in the Singapore tile had 7.22% (Saltcoats) and 13.13% (Blackness) higher humidity on average than the tile surface. The microhabitat also had lower humidity variance than all other designs (3.96% variance for humidity at Blackness and 7.36% at Saltcoats). This trend was consistent at the Isle of Wight where the Art 1 tile microhabitats had higher humidity and lower temperature than all tile designs (excluding clearings), with the exception of the Art 2 microhabitat ($p < 0.001$).

4. Discussion

Tiles with “Intermediate” levels of complexity (modifications at the mm-scale) were found to be most suitable for barnacle colonisation, especially at the Isle of Wight and Blackness sites. This scale of complexity likely allows cyprids to settle in greater densities with little distance between individuals (Crisp, 1961). Across the full range of textures, the smoothed concrete of the plain-cast control tiles had significantly fewer barnacles than the textured designs. However, the most complex Singapore design also had statistically fewer numbers of barnacles compared with the intermediate textured designs. Intermediate complexity (mm-scale) was notably lacking on the high complexity (cm-scale) Singapore tiles, so whilst this design provides greater habitat for other gastropod species, its relatively smooth surface renders it

unsuitable for barnacles. Smooth surfaces resulted in decreased barnacle recruitment and colonisation and are poor surrogates for the surface roughness characteristics of natural rocky shores (Coombes et al., 2015), characteristics mimicked by tiles with intermediate surface complexity.

Of the intermediate designs, the grooved texture design was consistently shown to be optimal for early recruitment and subsequent colonisation of barnacles despite all 3 sites having differing environmental contexts. The grooved tiles had a series of intermediate scale ridges that were ideally sized for the approximate 0.5 – 1.0 mm width of barnacle cyprids (Coombes et al., 2015) with barnacles observed to be growing uniformly inside these ridges at each site. This pattern of uniform colonisation was also observed on the barnacle tile, which had a similar scale of complexity. Creating complexity at the mm-scale for barnacles is important in the design of coastal structures because barnacles provide a bioprotective function by forming a protective layer that reduces both thermal and salt damage to the structure (Coombes et al., 2017). The significant differences between the plain-cast and intermediate complexity designs at each site, especially in the early stages of recruitment (2–6 months post-installation), emphasises the importance of surface texture in the initial recruitment of barnacles.

The influence of texture on barnacle colonisation varied with site, likely resulting from differences in the local supply of larvae (Minchinton and Scheibling, 1991). Large increases in barnacles between months 0–1 and 11–13 are likely associated with *Semibalanus*

balanoides and increases later in the year are possibly associated with settling *Autrominius modestus* or *Chthamalus montagui*. Barnacle cyprids are known to be less selective at high densities, favouring the availability of free space (Kent et al., 2003) and even settling on seaweed in extreme circumstances. The much higher barnacle occupancy of tiles at Blackness likely resulted in preferred attachment sites filling up faster and producing an apparent greater affinity of larvae for less complex tiles. In contrast, the lower baseline cover of barnacles at Saltcoats and the Isle of Wight may result in a positive density dependence with barnacles more likely to be free to colonise their preferred attachment sites. Given the gregarious nature of barnacle settlement (e.g. Kent et al., 2003) the presence of numerous nearby barnacles, as indicated by the baseline survey, would have also further promoted more rapid colonisation of the cleared areas at the Blackness site.

Increasing the attractiveness of the structure to barnacle larvae, by adding intermediate levels of complexity (mm-scale grooves etc.), will result in more consistent annual settlement, an important factor in maximising the bioprotective function of barnacles and the wider ecological and community development benefits they provide. For example, the presence of live and dead barnacles creates habitat and provides structure for other organisms to settle (biogenic habitat) (Smith et al., 2014). These habitat-forming organisms encourage the settlement of *Fucus* zoospores (Van Tameelen and Stekoll, 1997), provide habitat for small gastropod species, such as littorinids and other marine fauna that utilise the empty shells (Cartwright and Williams, 2012). Their presence also reduces surface temperatures and attenuates the impact of other intertidal stressors such as wave action and desiccation (Rickards and Boulding, 2015). In combination, these effects result in greater abundance and diversity of functional groups within biogenic habitats than would occur in areas that lack them (Harley, 2006).

Surface roughness also influences the composition and functioning of ecological communities (Firth et al., 2014b). Variation in width and depth of pits and holes in the Singapore tile design produced optimal species richness and abundance of mobile species where this design was installed. This was particularly noticeable at Saltcoats, where, after 18 months, the maximum species richness on the Singapore tile exceeded the baseline. During monitoring, there was also a greater diversity of species found in higher abundances than those recorded in the baseline. This higher level of complexity has been shown to link to greater macroinvertebrate abundance and results in more diverse communities than smoother surfaces (Moschella et al., 2005; Prendergast et al., 2009), even when surface area was subject to experimental control (Loke and Todd, 2016). Few sessile species apart from barnacles were recorded. However, low abundance *Fucus* colonisation on a few tiles at Saltcoats from between 6 and 18 months promises the development of a more diverse community given time. This high level of complexity also positively and significantly moderated the microclimate (temperature and humidity) compared to all other designs at the two Scottish sites. Tiles with microhabitats at Saltcoats had the additional benefit of maintaining a more optimal microclimate on the tile surfaces and likely contributes to the higher species richness and abundance recorded on Singapore tiles.

Despite its high cm-scale structural complexity, the Singapore tile design did not recruit many barnacles and reduced the potential for barnacles to facilitate further community development as well as providing biogenic habitat (Thompson et al., 1996). In addition, although all tiles lacked water retention capacity, increasing the angle between the Singapore tile surface and the pits would enable the tile to retain water, which would further improve biodiversity, microclimate and refuge availability under stressful intertidal conditions (Browne and Chapman, 2011; Evans et al., 2016). Moving forward, the most suitable design – to optimise for species richness and abundance and for the ecosystem engineering and bioprotective capabilities of barnacles – would be a hybrid design incorporating the cm-scale microhabitats of the Singapore design with the mm-scale grooved or barnacle designs.

5. Conclusions

We demonstrate here that enhancing hard coastal marine engineering structures by using surface designs with intermediate scale complexity of mm-scale roughness promotes more rapid barnacle colonisation. This leads to fine-scale biogenic habitat creation and favours the development of more diverse assemblages. The addition of microhabitats at the scale of 10–30 mm in depth and widths, improves species richness and abundance on hard vertical coastal defences by providing habitat that would otherwise have been absent. Tiles with the highest level of complexity and the most microhabitats also positively moderated the microclimate of the whole tile by lowering temperatures and raising humidity. Thus, the highest levels of complexity provide both physical habitat and microclimate buffering, improving habitat quality by reducing desiccation stress during low tide. While this investigation has shown the addition of microhabitats to make a difference for species richness, abundance, and microclimate moderation, ongoing monitoring is needed to determine the influence of these designs on ecology and asset resilience over longer timescales that better match the design life of typical hard engineering structures (~80–100 years).

Additionally, detailed baseline studies should be in place before the selection of ecological enhancement designs. These designs may perform differently in different contexts and so should be judged against engineering function and any ecological and biodiversity enhancements that might be encouraged or required by statutory agencies as best practice and/or mitigation measures. Urgent attention should also be given to identifying multi-scale designs to optimise for sessile and mobile species abundance and richness, to improve the habitat value of the engineering structure itself as well as to partially offset any future habitat/species loss predicted under climate change. Trials of these designs are also needed at engineering scale, so that both the ecological value of the enhancements and the engineering practicalities of building them into replacement or new engineering schemes can be identified.

To our knowledge, this experiment represents one of the largest trials of multiple tile designs at various sites to date in the UK. The results provide useful insights on the kinds of ecological responses that can be expected by manipulating surface topography at various scales. This informs biogeomorphological (two-way interactions between organisms and their habitat) and ecological concepts, showing strong relationships between geomorphic complexity and species response, and at species level, that larval density appears to influence colonisation patterns. More practically, results from a trial of this scale improves the scientific confidence (e.g. Evans et al., 2019) of widespread, commercial scale application and operational practice of these types of ecological enhancements. The results reported here inform an emerging trend in policy and practice of promoting ‘greening the grey’ (Naylor et al., 2017), evidenced in the forthcoming Natural and Nature-based Solutions international guidelines (Engineering With Nature, 2018) and policy windows (Brown et al., 2017; Rose et al., 2017) aimed at influencing revisions to key biodiversity, climate change adaptation and green infrastructure policy worldwide. The enhancements studied here are of value where other, more natural, nature-based solutions are not socially, economically or technically feasible and where the policy decision requires use of hard coastal structures.

Conflicts of interest

The authors declare no conflict of interest.

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Appendix

Table A1

Summary of significant post-hoc comparisons for barnacle cover (%) between tile types in each month after installation at each site. Saltcoats used a GLS model and LME models were used for the Isle of Wight and Blackness.

Site/Month	Comparison	SE	df	T ratio	Direction	P value
Saltcoats 2	Art 2- Control	0.276	215	6.894	>	***
	Art 2- Geotile	0.364	215	4.091	>	**
	Art 2- Singapore	0.276	215	7.029	>	***
	Art 3- Control	0.377	215	5.582	>	***
	Art 3- Geotile	0.445	215	3.790	>	**
	Art 3- Singapore	0.376	215	5.675	>	***
	Clearing- Control	0.460	215	3.879	>	**
	Clearing- Singapore	0.460	215	3.952	>	**
	Control- Grooved	0.356	215	-4.624	<	***
Saltcoats 6	Grooved- Singapore	0.355	215	4.722	>	***
	Art 2- Control	0.219	215	9.025	>	***
	Art 2- Geotile	0.216	215	4.979	>	***
	Art 2- Singapore	0.216	215	9.075	>	***
	Art 3- Control	0.294	215	6.945	>	***
	Art 3- Geotile	0.341	215	4.262	>	***
	Art 3- Singapore	0.292	215	6.936	>	***
	Barnacle- Control	0.358	215	3.882	>	**
	Barnacle- Singapore	0.356	215	3.847	>	**
	Clearing- Control	0.347	215	4.552	>	***
	Clearing- Singapore	0.344	215	4.521	>	***
	Control- Grooved	0.274	215	-6.468	<	***
	Geotile- Grooved	0.324	215	-3.654	<	**
	Grooved- Singapore	0.271	215	6.458	>	***
Saltcoats 12	Art 2- Control	0.293	215	7.127	>	***
	Art 2- Geotile	0.396	215	3.125	>	*
	Art 2- Singapore	0.277	215	7.182	>	***
	Art 3- Control	0.410	215	4.771	>	***
	Art 3- Singapore	0.398	215	4.657	>	***
	Barnacle- Control	0.451	215	3.162	>	*
	Clearing- Control	0.406	215	3.120	>	*
	Control- Grooved	0.347	215	-5.655	<	***
Saltcoats 18	Grooved- Singapore	0.334	215	5.585	>	***
	Art 2- Control	0.469	215	4.688	>	***
	Art 2- Singapore	0.443	215	4.564	>	***
	Control- Grooved	0.560	215	-3.851	<	**
IOW 2	Grooved- Singapore	0.538	215	3.675	>	**
	Art 1- Art 3	3.195	219	-5.114	<	***
	Art 1- Clearing	3.117	219	-3.976	<	**
	Art 1- Control	3.712	219	5.431	>	***
	Art 1- Grooved	3.307	219	-4.077	<	**
	Art 2- Control	3.569	219	7.989	>	***
	Art 2- Geotile	2.988	219	5.226	>	***
	Art 3- Barnacle	3.251	219	4.151	>	**
	Art 3- Control	3.668	219	9.950	>	***
	Art 3- Geotile	3.107	219	7.595	>	***
	Barnacle- Control	3.759	219	6.119	>	***
	Barnacle- Geotile	3.214	219	3.144	>	*
	Barnacle- Grooved	3.361	219	-3.165	<	*
	Clearing- Control	3.601	219	9.040	>	***
	Clearing- Geotile	3.028	219	6.492	>	***
	Control- Geotile	3.635	219	-3.548	<	*
	Control- Grooved	3.755	219	-8.933	<	***
IOW	Geotile- Grooved	3.222	219	-6.437	<	***
	Art 1- Art 2	2.303	219	-5.757	<	***

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Table A1 (continued)

Site/Month	Comparison	SE	df	T ratio	Direction	P value
6	Art 1- Art 3	2.420	219	-7.423	<	***
	Art 1- Barnacle	2.525	219	-3.427	<	*
	Art 1- Clearing	2.348	219	-4.853	<	***
	Art 1- Control	3.009	219	7.209	>	***
	Art 1- Grooved	2.533	219	-7.864	<	***
	Art 2- Control	2.877	219	12.150	>	***
	Art 2- Geotile	2.214	219	6.433	>	***
	Art 3- Barnacle	2.478	219	3.758	>	***
	Art 3- Control	2.972	219	13.343	>	***
	Art 3- Geotile	2.335	219	8.115	>	***
	Barnacle- Control	3.058	219	9.923	>	***
	Barnacle- Geotile	2.444	219	3.944	>	**
	Barnacle- Grooved	2.589	219	-4.353	<	***
	Clearing- Control	2.914	219	11.355	>	***
	Clearing- Geotile	2.261	219	5.477	>	***
	Clearing- Grooved	2.417	219	-3.526	<	*
	Control- Geotile	2.943	219	-7.035	<	***
	Control- Grooved	3.065	219	-13.577	<	***
	Geotile- Grooved	2.452	219	-8.525	<	***
IOW 12	Art 1- Art 2	3.248	219	-6.346	<	***
	Art 1- Art 3	3.321	219	-6.141	<	***
	Art 1- Barnacle	3.571	219	-4.862	<	***
	Art 1- Clearing	3.168	219	-3.124	<	*
	Art 1- Control	4.854	219	4.944	>	***
	Art 1- Grooved	3.592	219	-8.232	<	***
	Art 2- Clearing	2.675	219	4.006	>	**
	Art 2- Control	4.547	219	9.811	>	***
	Art 2- Geotile	2.764	219	4.409	>	***
	Art 3- Clearing	2.758	219	3.806	>	**
	Art 3- Control	4.603	219	9.645	>	***
	Art 3- Geotile	2.845	219	4.208	>	**
	Barnacle- Control	4.786	219	8.641	>	***
	Barnacle- Grooved	3.492	219	-3.496	<	*
	Clearing- Control	4.493	219	7.543	>	***
	Clearing- Grooved	3.079	219	-6.389	<	***
	Control - Geotile	4.547	219	-7.130	<	***
	Control - Grooved	4.802	219	-11.156	<	***
	Geotile- Grooved	3.157	219	-6.698	<	***
IOW 18	Art 1- Art 2	5.441	219	-5.140	<	***
	Art 1- Art 3	5.501	219	-4.151	<	**
	Art 1- Barnacle	5.909	219	-4.413	<	***
	Art 1- Control	7.998	219	3.288	>	*
	Art 1- Geotile	5.374	219	-3.320	<	*
	Art 1- Grooved	5.943	219	-6.600	<	***
	Art 2- Clearing	4.426	219	4.420	>	***
	Art 2- Control	7.483	219	7.252	>	***
	Art 3- Clearing	4.489	219	3.215	>	*
	Art 3- Control	7.529	219	6.525	>	***
	Art 3- Grooved	5.283	219	-3.103	<	*
	Barnacle- Clearing	4.980	219	3.549	>	*
	Barnacle- Control	7.832	219	6.687	>	***
	Clearing- Control	7.347	219	4.723	>	***
	Clearing- Grooved	5.021	219	-6.139	<	***
	Control- Geotile	7.436	219	-5.935	<	***
	Control- Grooved	7.858	219	-8.339	<	***
	Geotile- Grooved	5.151	219	-4.152	<	**
Site	Comparison	SE	df	T ratio	direction	P value
Blackness 2	Art 1- Barnacle	6.503	196	-8.156	<	***
	Art 1- Clearing	7.606	196	-6.736	<	***
	Art 1- Geotile	6.730	196	-6.588	<	***
	Art 1- Grooved	6.663	196	-9.714	<	***
	Barnacle- Control	6.606	196	6.618	>	***
	Barnacle- Singapore	7.366	196	8.822	>	***
	Clearing- Control	7.700	196	5.444	>	***
	Clearing- Singapore	8.343	196	7.574	>	***
	Control- Geotile	6.832	196	-5.126	<	***
	Control- Grooved	6.765	196	-8.189	<	***
	Geotile- Grooved	4.759	196	-4.282	<	***
	Geotile- Singapore	7.562	196	7.443	>	***
	Grooved- Singapore	7.504	196	10.216	>	***

(continued on next page)

Table A1 (continued)

Site/Month	Comparison	SE	df	T ratio	Direction	P value
Blackness 6	Art 1- Barnacle	3.369	196	-11.137	<	***
	Art 1- Clearing	3.947	196	-7.488	<	***
	Art 1- Geotile	3.479	196	-9.285	<	***
	Art 1- Grooved	3.447	196	-12.580	<	***
	Art 1- Singapore	4.902	196	3.729	>	**
	Barnacle- Control	3.376	196	8.494	>	***
	Barnacle- Singapore	4.077	196	13.684	>	***
	Clearing- Control	3.947	196	5.248	>	***
	Clearing- Grooved	2.941	196	-4.695	<	***
	Clearing- Singapore	4.560	196	10.492	>	***
	Control- Geotile	3.484	196	-6.735	<	***
	Control- Grooved	3.452	196	-10.000	<	***
	Control- Singapore	4.901	196	5.534	>	***
	Geotile- Grooved	2.249	196	-4.917	<	***
	Geotile- Singapore	4.166	196	12.141	>	***
	Grooved- Singapore	4.140	196	14.889	>	***
Blackness 12	Art 1- Barnacle	3.665	196	-7.565	<	***
	Art 1- Geotile	3.725	196	-6.635	<	***
	Art 1- Grooved	3.706	196	-8.066	<	***
	Art 1- Singapore	5.809	196	3.834	>	**
	Barnacle- Clearing	2.261	196	5.239	>	***
	Barnacle- Control	3.247	196	5.908	>	***
	Barnacle- Singapore	4.620	196	10.823	>	***
	Clearing- Geotile	2.357	196	-3.750	<	**
	Clearing- Grooved	2.326	196	-6.024	<	***
	Clearing- Singapore	5.047	196	7.560	>	***
	Control- Geotile	3.314	196	-4.880	<	***
	Control- Grooved	3.292	196	-6.484	<	***
	Control- Singapore	5.558	196	5.545	>	***
	Geotile- Grooved	1.310	196	-3.950	<	**
	Geotile- Singapore	4.667	196	10.067	>	***
	Grooved- Singapore	4.652	196	11.213	>	***
Blackness 18	Art 1- Barnacle	4.733	196	-4.648	<	***
	Art 1- Geotile	4.801	196	-4.223	<	***
	Art 1- Grooved	4.778	196	-4.606	<	***
	Art 1- Singapore	7.408	196	3.322	>	*
	Barnacle- Clearing	2.862	196	4.933	>	***
	Barnacle- Control	4.127	196	3.303	>	*
	Barnacle- Singapore	5.858	196	7.957	>	***
	Clearing- Geotile	2.980	196	-4.160	<	***
	Clearing- Grooved	2.942	196	-4.804	<	***
	Clearing- Singapore	6.398	196	5.078	>	***
	Control- Grooved	4.181	196	-3.263	<	*
	Control- Singapore	7.048	196	4.679	>	***
	Geotile- Singapore	5.914	196	7.590	>	***
	Grooved- Singapore	5.895	196	7.908	>	***

Table A2

Summary of significant post-hoc comparisons for species richness between tile types at 18 months after installation at each site. All sites used GLS models for species richness. Df based on full model analysis.

Site	Comparison	SE	df	T ratio	Direction	P value
Saltcoats 18	Art 2- Singapore	0.449	215	-5.492	<	***
	Art 3- Singapore	0.509	215	-5.858	<	***
	Barnacle- Singapore	0.459	215	-7.032	<	***
	Clearing- Singapore	0.449	215	-7.090	<	***
	Control- Singapore	0.449	215	-7.496	<	***
	Geotile- Singapore	0.480	215	-7.091	<	***
	Grooved- Singapore	0.449	215	-7.458	<	***
IOW 18	Art 1- Control	0.134	226	3.973	>	**
	Art 2- Control	0.149	226	3.795	>	**
	Art 3- Control	0.136	226	3.241	>	*
Blackness 18	Barnacle- Singapore	0.288	203	-4.227	<	***
	Geotile- Singapore	0.288	203	-4.171	<	***

Table A3
Summary of significant post-hoc comparisons for mobile abundance between tile types at 18 months after installation at each site. All sites used GLS models for mobile species abundance. Df based on full model analysis.

Site	Comparison	SE	df	T ratio	Direction	P value
Saltcoats 18	Art 2- Barnacle	0.272	215	5.286	>	***
	Art 2- Control	0.284	215	5.652	>	***
	Art 2- Geotile	0.284	215	5.719	>	***
	Art 2- Grooved	0.297	215	4.305	>	***
	Barnacle- Singapore	0.337	215	-5.461	<	***
	Control- Singapore	0.346	215	-5.788	<	***
	Geotile- Singapore	0.347	215	-5.844	<	***
	Grooved- Singapore	0.357	215	-4.701	<	***
IOW 18	Art 1- Control	0.362	226	4.497	>	***
	Art 2- Control	0.416	226	4.547	>	***
	Art 3- Control	0.244	226	6.831	>	***
	Barnacle- Control	0.302	226	4.235	>	***
	Clearing- Control	0.250	226	4.535	>	***
	Control- Geotile	0.303	226	-4.463	<	***
	Control- Grooved	0.293	226	-4.831	<	***
Blackness 18	Barnacle- Grooved	0.344	203	-4.275	<	***
	Barnacle- Singapore	0.249	203	-3.998	<	**



Fig. A1. Location of field sites and installation strategy at Blackness Castle, Saltcoats and Shanklin, Isle of Wight.

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